The Emission of Electricity from Carbon at High Temperatures.

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(Received January 30,—Read February 8, 1912.)

(From the National Physical Laboratory.)

Introductory.

This paper is a first communication of the results of some experiments conducted in electric furnaces at atmospheric pressure, and mostly at very high temperatures. The investigation came about originally in an attempt to explain some contamination phenomena which were encountered when short tubes of extremely refractory rare earths were baked in various types of carbon-tube resistance furnaces at temperatures from 1500° C. upwards.

An examination of the refractory tubes after baking showed that, in certain circumstances, the outer surface of each tube, instead of having the white and hard appearance of the rest, was carburised and crumbly. The action was not merely a surface one, but extended to an appreciable depth. On the other hand, the inner surface of the tube was comparatively unaffected, although it was freely open to the furnace gases, nor did the blackening occur if the tube was shielded. An explanation which at once suggests itself is that the blackening was produced by particles—possibly electrified—shot off from the carbon walls of the furnace with sufficient velocity to penetrate the material of the refractory tubes some millimetres (4 to 7) away. The circumstances pointed to the desirability of a general study of the electrical properties of the atmospheres of such furnaces.

Historical.

Negative Electricity.—So far as we know, practically no experiments have been conducted with carbon at pressures approaching atmospheric, but at low pressures the emission of negative electricity from hot carbon has been investigated systematically by O. W. Richardson (1903, *et seq.*),* H. A. Wilson (1904),† Deininger (1907),‡ and very recently by Pring and Parker (1912).§ The ionisation currents have been generally attributed to the liberation of corpuscles from the hot carbon; the magnitude of the

* Richardson, 'Phil. Trans.,' 1903, A, vol. 201, p. 497; 1908, vol. 207, p. 1.

† Wilson, 'Phil. Trans.,' 1904, A, vol. 202, p. 243.

‡ Deininger, 'Deutsch. Physik. Gesell.,' 1907, vol. 9, p. 674.

§ Pring and Parker, 'Phil. Mag.,' Jan., 1912.

effect is largely influenced by the pressure and nature of the residual gas. Richardson obtained from a carbon filament at low pressures currents from 10^{-8} to 2 ampères per square centimetre. He found that the relation between ionisation and temperature for carbon (as well as for some other bodies) could be expressed by the formula*

$$i = a\theta^{\frac{1}{2}}e^{-b/\theta},$$

where i is the saturated ionisation current, θ is the absolute temperature, and a and b are constants for the substance. (For carbon, $a = 10^{34}$ and $b = 98{,}000$.) Wilson and Deininger each subscribed to Richardson's formula; but Pring and Parker, as the result of experiments on purified carbon at extremely low pressures, impeach the truth of the formula, and affirm that the large ionisation currents obtained by previous observers are due to the emission of corpuscles not from the carbon itself, but rather from some high-temperature reaction between the carbon (or its contained impurities) and the residual gas. Their results show that the negative ionisation from heated carbon falls off continuously both with reduction of pressure and with progressive purification of the carbon.

Positive Electricity.—So far as we know, a similar emission of positive electricity has not been detected with carbon at atmospheric pressure.† But in the case of incandescent metals at atmospheric pressure, Guthrie,‡ as far back as 1873, referred to an experiment which, according to modern views, shows that an iron ball in air at atmospheric pressure emits positive electricity when red hot, and negative electricity when white hot—a result now well known. Elster and Geitel (1883, *et seq.*)‡ got much the same sort of effect with a platinum wire at atmospheric pressure; the ionisation currents were of electrometer magnitude, and their direction and amount were considerably affected by the nature of the surrounding gas.

"*Sputtering.*"—The various phenomena are further complicated by the vaporising or "sputtering" of the hot metal or carbon—an actual transport of material, which is more marked when the substance is negatively charged and the pressure is reduced. The nature of the surrounding gas

* Richardson's formula, though deduced from theoretical considerations, is of the type which was used by Kirchhoff, Rankine, and Dupré to connect vapour pressure (p) with absolute temperature (θ),

$$\log p = A + B \log \theta + C/\theta.$$

This latter formula, it may be noted, is elastic and allows considerable latitude in the relative values of the constants without impairing its efficiency.

† J. J. Thomson ('Phil. Mag.,' 1899, vol. 48, p. 547) found that a carbon lamp filament gave a positive leak so long as occluded gas was being expelled.

‡ See J. J. Thomson's 'Conduction of Electricity through Gases,' 2nd edit., p. 188, for a complete bibliography.

also affects the disintegration considerably. The carriers appear to consist of small molecular aggregates.* In the case of cathodic sputtering, they are negatively charged.

Thus the electrification produced by an incandescent solid is depends on :—

1. The nature and temperature of the solid.

2. The nature and pressure of the surrounding gas; and it is evident that the phenomena under the conditions of the present experiment will not be of a simple character.

Experimental.

The type of electric furnace employed in nearly all the present experiments consisted of a straight carbon tube heated by alternating current. Some of the details of a small furnace of this type are shown in fig. 1. A

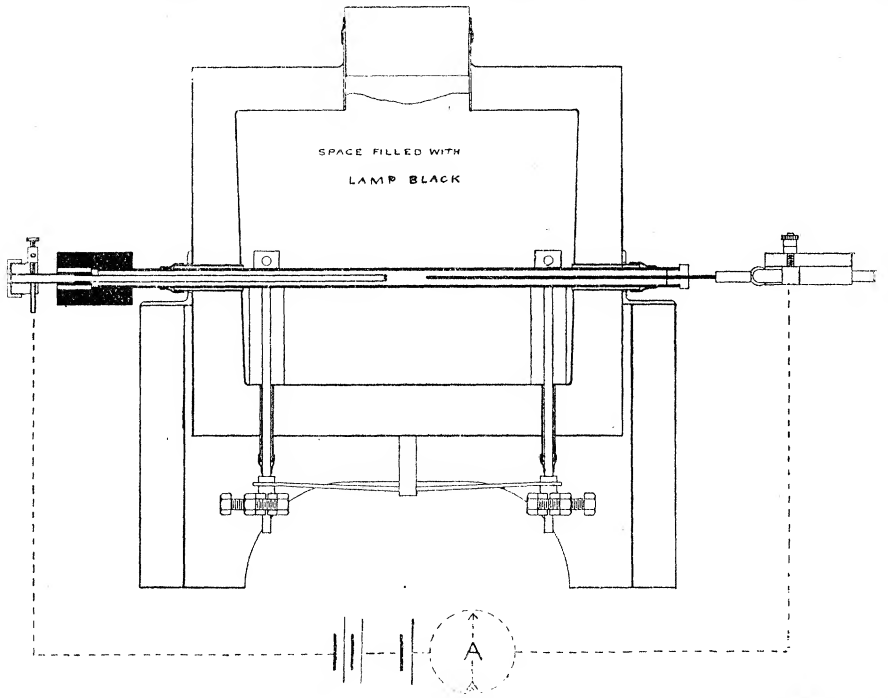

FIG. 1.—Small model Straight Carbon-tube Furnace, with Pyrometer Sighting Tube and movable Electrode in position for Determination of Potential-current Curves.

* The sputtering of iridium at temperatures from 1400° upwards is notorious, and Reboul and de Bollemont ('Compt. Rend.,' Mar. 20 and Oct. 2, 1911) have recently shown that both copper and silver, when heated in a furnace at temperatures from 500 to 1000° C., give a sputtered image having the outline of the emitting metal on screens up to 2 mm. away in air at atmospheric pressure. No potential was applied. The amount of the deposit increases with the temperature and varies with the surrounding gas. They put forward the view that the sputtering is associated with the known emission of positive electricity when these metals are heated.

second form was made up of a graphite spiral heater having an insulated liner-tube of carbon similar to the conductor used in the first type of furnace. This is illustrated in fig. 2. In both furnaces the heater was surrounded by very pure lamp black, with an outer lagging of magnesia brick.

The *graphite* used in the experiments was the usual grade of Acheson graphite made at Niagara. In one instance, analysis showed it to be of a purity of about 99·8 per cent. carbon. The graphite tubes were drilled from solid rods and after a little experience the heating spirals of the second type of furnace were easily cut from the solid to any dimensions by the use

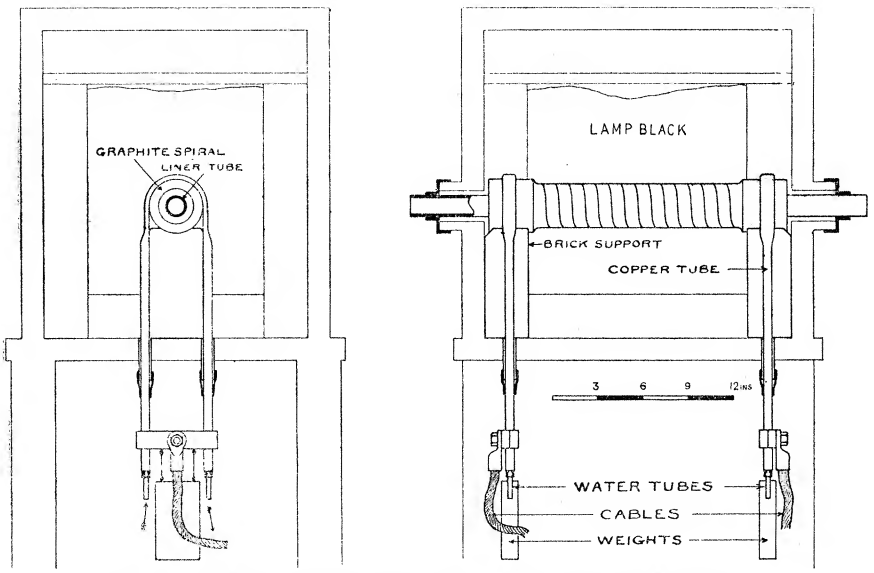

FIG. 2.—Carbon Spiral Furnace, for temperatures up to 2500° C.

of an appropriate lathe; graphite, unlike amorphous carbon, is an extremely tractable material to machine.

The *carbon* tubes were supplied by the General Electric Company's Witton Works, Birmingham, and were of a purity higher than the average, but usually contained a little under 1 per cent. of foreign matter (iron, silica, and alumina). A good deal of this, however, was usually removed previous to use in the experiments by heating for some time to a very high temperature in a current of nitrogen.

The experiments were carried out in the Thermometry Department of the National Physical Laboratory, where a newly installed plant, specially designed for electric furnace work, was to hand. The power supplies available are a 100 volt D.C. circuit, giving currents up to 600 ampères, and

a motor alternator of 15 kilowatts capacity with extra large range of regulation and capable of giving voltages up to 500 and frequencies from 80 to 200. Low-frequency alternating current up to 250 ampères at 30 to 60 cycles at a fixed voltage of about 70 can be got from slip-rings on the motor.

By means of a transformer having a number of variable ratios, alternating current can be obtained up to 250 ampères at 20 volts or 2000 ampères at 2 volts. The regulating devices are such that any temperature attainable in a furnace can be kept constant as long as desired.*

Many of the details of this unusually complete equipment are due to Mr. C. G. Eden, now of the Aeronautics Division of the National Physical Laboratory. We wish to acknowledge our great indebtedness to him, not only for his work in this connection, but also for his active co-operation in the earlier experiments.

Potential-current Curves.

The initial experiments were directed to a determination of the current-voltage curves for two insulated carbon rod electrodes projecting within the furnace one from each end, and in alignment, as shown in fig. 1. The distance between them could be varied as desired. By means of copper clips and low resistance leads they were connected at their outer ends† with a battery of variable E.M.F. and a current-measuring device of many overlapping ranges capable of reading from a micro-ampère to 50 ampères. One electrode was hollow and through it was sighted a Siemens optical pyrometer, suitable for the measurement of temperatures up to 3000° C.

Access of air to the interior of the furnace was prevented by thin mica windows, and a current of any required gas, in most cases nitrogen, could be passed through when desired.‡ In all the experiments dealt with in this paper, the pressure remained atmospheric.

With small potentials (up to 6 or 8 volts) applied to the electrodes, no appreciable current could be detected at temperatures below about 1400° C., but as the temperature rose the current became measurable and rapidly increased until at about 2000° it reached a value of several ampères. The

* A detailed description of the furnaces and other electro-technical equipment used in this research is being prepared for publication elsewhere, and to this source reference must be made for further details.

† The outer ends of the electrodes remained perfectly cool and there was no question of any thermo-electric disturbances between the carbons and the copper leads.

‡ The passage of a current of gas was absolutely necessary while temperature measurements above 1800° were being made, in order to remove the slight fog which always accumulates in the sighting tube if any impurities are present in the carbon.

highest current recorded was 10 ampères. Fig. 3 will give a notion of some of the curves obtained at different temperatures for electrodes 1 cm. apart. At the lower temperatures the ionisation currents attain—curiously enough for such a high pressure and currents of this magnitude—what appear to be saturation values with quite small applied voltages. As far as the experiments go, the curves at the higher temperatures show the same character

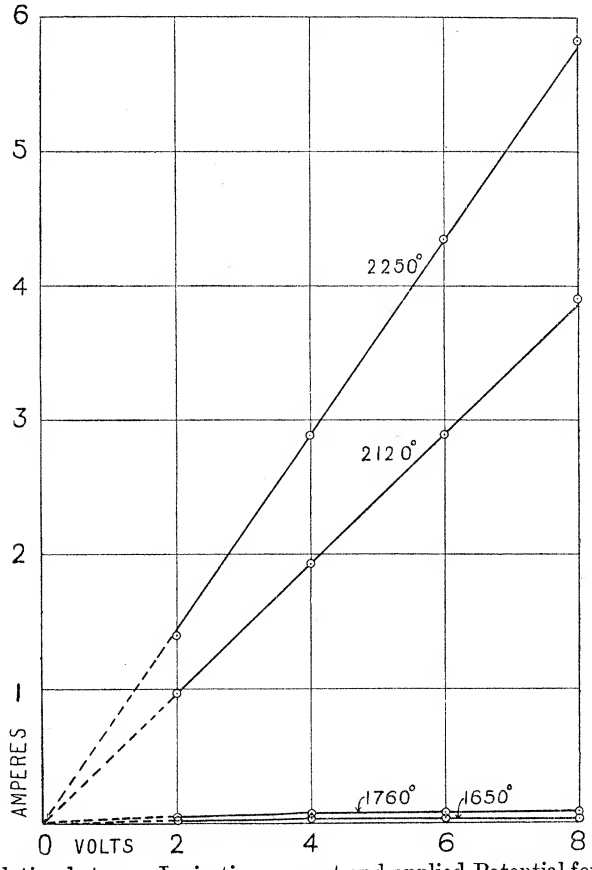

FIG. 3.—Relation between Ionisation-current and applied Potential for a 1-cm. gap between the electrodes.

with higher potentials; with small voltages, there is a linear relation between potential and current, as will be seen.*

Ionisation and Temperature.

The continuous curve of fig. 4 shows a relation between ionisation-current and temperature for an applied potential of 2 volts on a 1-cm. gap between

* This experiment was shown by Mr. Eden and one of us at the Royal Society Conversazione of May, 1911.

the electrodes. As will be seen, the curve is exponential in character,* but as the currents make no pretence of being saturated, the actual numbers have no great quantitative interest. The points indicated (by small circles) were not all obtained in the one experiment but on different days with the same apparatus. The dotted straight line was obtained by plotting the logarithm of the current against temperature.

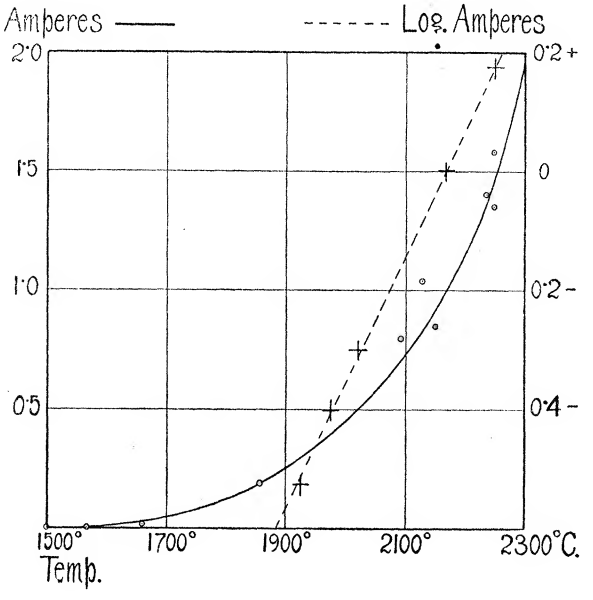

FIG. 4.—The full-line curve shows a relation between ionisation-current and temperature for an applied potential of 2 volts on a 1-cm. gap between the electrodes. The dotted straight line is plotted from log. of the current and temperature.

Ionisation Current and Length of Gap.

The table adjoining indicates how the current varies with the distance between the electrodes for an applied potential of 2 volts. The results are set out in fig. 5. The full-line curves are plotted to the left-hand scale of current; the dotted lines to the right-hand scale. It will be noticed that the effective resistance of the gap increases, but not very much, with the distance between the electrodes. The explanation of this is given later, on p. 388.

* The curve is very fairly represented by $i = 1{\cdot}55 \times 10^{-5} e^{0{\cdot}00513\theta}$, where i is the current in ampères and θ the temperature on the centigrade scale.

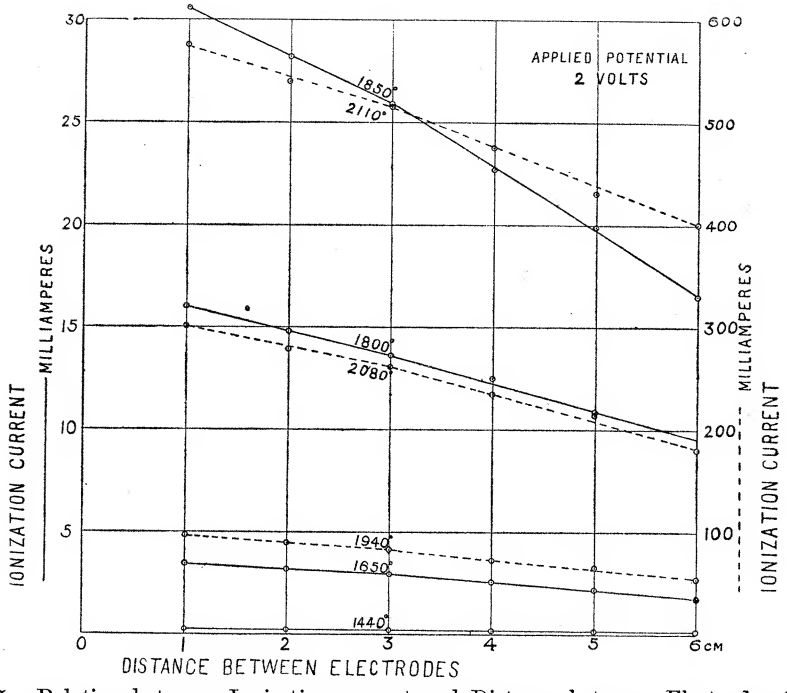

FIG. 5.—Relation between Ionisation-current and Distance between Electrodes for an applied Potential of 2 volts. The full-line curves are plotted to the left-hand scale of current; the dotted lines to the right-hand scale.

Table I.—Applied Potential, 2 volts.

Distance between electrodes.	1440° C.	1650°.	1800°.	1850°.	1940°.	2080°.	2110°.
cm.	milli-ampère.	milli-ampères.	milli-ampères.	milli-ampères.	milli-ampères.	milli-ampères.	milli-ampères.
1	0·22	3·40	16·0	30·6	96·2	301	575
2	0·21	3·18	14·8	28·2	89·5	278	540
3	0·19	2·92	13·6	25·9	82·5	261	515
4	0·18	2·59	12·5	22·7	72·5	234	475
5	0·16	2·20	10·9	19·9	65·2	214	430
6	0·13	1·75	9·0	16·5	54·0	180	400

The Magnitude of the Ionisation.

The magnitude of the ionisation currents indicated that, although the pressure was atmospheric, the atmosphere of the furnace was ionised to an unusual degree at high temperatures. The possibility of some sort of leakage and rectification-effect from the alternating heating current was tested and dismissed, as it was found that the ionisation currents persisted

when the furnace current was temporarily shut off. Before testing the effect of temperature in the absence of an external source of potential, we were led to try an experiment in which the furnace tube was heated by direct instead of alternating current. In these circumstances, we found a decided asymmetry in the amount of the ionisation current, depending on the direction of the external potential (which amounted to 2 volts). When the potential was such as to tend to send the current between the electrodes in the same direction as the heating current in the furnace tube, the resulting ionisation current was some four or five times bigger than when the external E.M.F. was reversed; in some cases the inequality was even more marked. Not only that, but the reading of the current-measurer was always in the same direction, no matter which way the outside battery was connected, *i.e.* the potential collected by the electrodes from the furnace was greater than the applied voltage. The outside battery was accordingly cut out, and the galvanometer now revealed currents of from 8 milliampères with a furnace temperature of 1660° to 34 milliampères at 1770°. The explanation is, doubtless, the greater electrical emissivity of the negative end of the furnace tube as compared with the positive end. The electrode within the negative end of the furnace becomes negatively charged with respect to the other electrode, and the resulting potential difference assists or retards the applied E.M.F. in a way which agrees with that actually found.

Hot and Cold Electrodes.

The next step was to try the effect of temperature alone in the absence of any directive influence of the heating current. Accordingly, one of the two insulated carbon electrodes was mounted as before within the central hot region of the alternating current furnace, while the other was arranged on a sliding carriage, so that (with a travel of about 6 inches) it could, at will, be placed either near the fixed electrode or some distance away, in the cooler part of the furnace tube. Thus, each time the movable electrode was shifted a large difference of temperature existed temporarily between the electrodes, and this manifested itself in the ammeter in the circuit as a transient current, which at 1400° amounted to 2 milliampères, and increased to nearly 2 ampères at 2500° C. When the movable electrode was pushed in, the current attained its maximum value pretty rapidly and died away as the two electrodes assumed the same temperature. The direction of the current was such that the cooler inserted electrode was positive with respect to the hotter fixed electrode. When the movable electrode was withdrawn into a cooler part of the furnace a current was again generated, but in the reverse direction. Such a reversal would

naturally not follow if the electrodes alone were concerned, but is easily explained if the furnace tube is taken into account. For the radial distance between the electrodes and the furnace tube was only some 8 mm.; so that, when the electrodes were separated, the easier path for the ionisation current was to bridge the two gaps between the electrodes and the furnace tube rather than cross the gas separating the electrodes. The hot fixed electrode remained at the same temperature (and potential) as the surrounding furnace tube and played no direct part in generating the current, but the hot movable electrode after being moved outward would emit negative electricity to the colder furnace tube, resulting in a reverse ionisation current as found.*

Similar results were obtained when the movable electrode was made the fixed, and *vice versâ*, and there was little difference in behaviour if graphite electrodes were substituted for carbon.

In view of the above explanation we carried out a pair of experiments, in one of which the inner ends of the carbon electrodes were inserted into carbon blocks of larger diameter, so that the distance between the electrodes and the furnace walls was reduced from about 8 mm. to 3 mm. In the other experiment the blocks were removed. Keeping the same distance between the electrodes, we found, as we expected, a larger ionisation current when the blocks were present than when they were absent. The currents were also of much longer duration owing to the extra time the blocks took to heat up and cool down. The part the furnace tube plays in these experiments explains the comparatively small variation of the resistance of the gap between the electrodes with its length (see p. 385).

The foregoing experiments were simplified by making a "poker" of a closed hollow carbon (or graphite) tube with an insulated co-axial rod of the same material inside it. When this was inserted into the furnace the outer sheath became hot first and a current passed across the intervening gas in the usual direction, from the cold rod to the hotter tube.

In several of these poker experiments we noticed a small initial "reverse" current, which soon died away and changed into a large current in the usual direction. This reverse current is doubtless due to positive ions which were emitted at the lower stages of the heating. The effect was not always obtained, and our experience up to now in these and further experiments has been that it is most marked with new carbon and diminishes with repeated heating. This is also the experience of workers with other substances than carbon; many experimenters, indeed, maintain an intimate connection

* By means of a device giving a suitable periodic movement to one electrode, a current generator constructed on this principle was shown at the reading of the paper.

between the emission of positive electricity and the evolution of absorbed gases, such as CO. In the case of carbon it may be related to the expulsion of some of the gaseous or more volatile impurities.

Non-electric Heating.

We felt that it would be of distinct interest to try to get some of the results put out above by methods of heating other than electric. The poker experiment last referred to was accordingly repeated, using a Méker gas furnace giving a temperature of about 1600° C. The largest negative* current obtained was 10 milliampères. Positive currents as large as 20 milliampères were also recorded, but owing to the oxidising nature of the atmosphere some combustion of the outer carbon tube occurred, and the results were at times a little obscure.

A second arrangement was tried in which the outside of a small poker (constructed essentially as before) was subjected to the flame of an oxy-acetylene burner. This has a temperature of some 2400° C. at the tip of the inner cone and is the hottest of all known flames. The heating was uneven and the currents obtained were unsteady; the highest value was about 1 milliampère in the usual direction, with occasional small "positive" currents.†

Water-cooled Electrodes.

We were now naturally desirous of converting the transient currents of the above experiments into steady currents, and to this end the following new arrangement was employed. An insulated brass tube, through which was sent a rapid current of water, was arranged along the axis of the furnace, and formed a cold electrode. The hot electrode was a surrounding co-axial insulated carbon tube, which received its heat from the furnace. The radial distance between the electrodes, both of which were stationary, was about 5 mm. and into this space hydrogen was continually passed, as it is known that this gas facilitates the passage of ions. As before, the electrodes were connected externally through a current-measurer and no potential was applied. The observations for a steadily rising temperature are shown in fig. 6. The carbon electrode was new and the first current recorded by the galvanometer was one which would be produced by positive ions crossing from the hot to

* *I.e.*, in the usual direction, from the cold electrode to the hot across the gap.

† We have since found that Dubs tried a similar experiment as long ago as 1888 ('Centralblatt. f. Elektrotechnik,' vol. 10, p. 749). He played a blowpipe flame on the lower of two carbon plates, one above the other and 1 mm. apart, and found (by the use of a "galvanoscope") that a weak current flowed from the cold to the hot plate across the gap. The effect was less with copper plates and was not detectable with iron.

the cold electrode (see p. 388). Afterwards the current reversed, attained a maximum in 17 minutes, and then dropped considerably. From 22 minutes onwards the current progressively increased with temperature and was in the neighbourhood of 0·4 milliampère for the last five minutes of the run, which had to be terminated owing to overheating of the furnace transformer, which at this stage was being greatly overloaded. On taking down the apparatus, the brass tube was found to be coated over most of its length with a deposit of carbon thick and coherent enough to be slid off in short lengths. Towards one

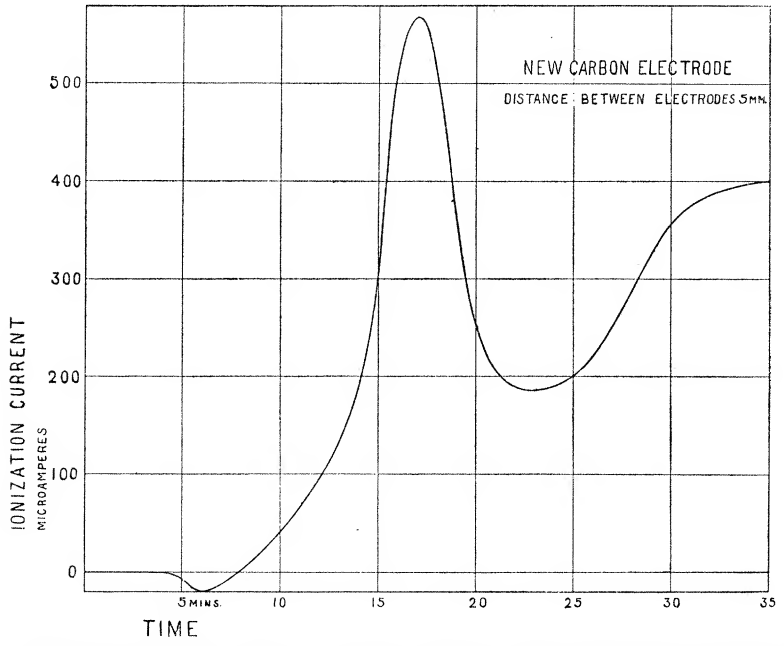

FIG. 6.—Relation between Ionisation current and Time with a steadily rising Temperature. The "cold" electrode was water-cooled; the "hot" electrode was of new carbon. No potential was applied.

end of the tube the deposit was rarer and whitish—presumably silica. This evidence of the distillation of both silica and carbon at atmospheric pressure is important. We associate the maximum negative current shown in fig. 7 with the passage of silicon and other impurities which are volatilised at about 2000° C. out of the carbon electrode. On a second heating, the maximum does not occur, and the ionisation current increases steadily with temperature. The transference of carbon from the hot electrode to the cold may prove to be a complete explanation not only of the contamination phenomena mentioned on p. 379, but also of the comparatively large accompanying currents. The point is being worked at and, should it appear that the ionisation currents

are due almost wholly to carbon vaporised or sputtered in this way, the experiment could probably be modified so as to yield an average value of the ratio of the charge to the mass for the carriers concerned.

It was apparent that the comparative smallness of the ionisation currents in the last experiment was due to insufficient temperature-difference between the electrodes, and steps were taken to remedy this. The furnace tube was taken out, and thinned over a short central region so as to render the heat, with the power available, more local and intense. The transformer was fitted with an air blast arrangement to keep it cool. The walls of the outer carbon electrode (which were rather thick) were also thinned considerably over the central region.

In the new run, neither positive rays nor a "negative" maximum was detected, but there was a general increase in the negative ionisation, the highest steady value being about 20 milliampères with the furnace near its upper limiting temperature of about 3000° C. A copious supply of hydrogen was found to be beneficial; the flow required nice adjustment, as too much gas cooled the furnace and was as bad as too little.

The Gas between the Electrodes.—Some interesting results came to light when the gas between the electrodes was varied. The following figures are abstracted from the note book :—

Rough value of temperature of hot electrode.*	Atmosphere.		
	Hydrogen.	Nitrogen.	Residual† furnace gas.
° C.	milliampères.	milliampères.	milliampères.
2000 ?	10	9	6
2300 ?	17	12	10
2400 ?	19	14	12
2500 ?	20	13	15

* In this particular arrangement, temperature measurements of any sort were very uncertain, and the figures given above must be considered only as the roughest estimates.

† Neither H_2 nor N_2 was supplied.

So far as these experiments go, there is not much difference between nitrogen and hydrogen at the lower temperatures; there is more at higher temperatures. But perhaps the most interesting feature of the observations is the large momentary increase in the ionisation that was obtained when a new gas was admitted into the space between the electrodes, *e.g.*, when hydrogen was admitted the current would leap up momentarily to half as much again as its ultimate steady value. The same thing occurred when nitrogen was the new gas. Now it is well known that acetylene, cyanogen,

methane, etc., can be synthesised at such temperatures, and it seems probable that on the entry of a new gas into the furnace momentary synthesis occurs when the proportions of the components are favourable, and that this production of C_2H_2, CH_4, C_2N_2, NH_3, or the like, is evidenced by an increase in the ionisation of the atmosphere. We hope to investigate this point further.

This particular experiment terminated eventfully in the fusion of the brass tube electrode. It was interesting to note that most of the water which streamed into the furnace (which was then at about 3000° C.) was immediately dissociated into hydrogen and oxygen, which burnt at one end of the furnace in a large blue flame, 2 feet long, coloured green at times with the vapour of brass.

Later Experiments.

In order to enhance the effect still further we have tried various modifications of the apparatus. To augment the electrode difference of temperature the hot electrode was removed, as we found that with alternating heating current the furnace tube could without prejudice be used as the hot electrode, provided, of course, that the "ionisation circuit" was carefully insulated. The brass water-cooled tube was sheathed with a larger carbon tube which served as the cold electrode, the whole being mounted as before along the axis of the furnace. The general cooling of the furnace was reduced in consequence, and with this arrangement we have obtained in different experiments steady currents of as much as 0·8 ampère for a few minutes, 0·2 ampère for half an hour, and 0·1 ampère for over an hour.

Fig. 7 illustrates one run obtained in a nitrogen atmosphere with new carbon electrodes. As the temperature rose, an initial small positive current of a few micro-ampères was succeeded by a large negative maximum amounting to 0·8 ampère. This diminished afterwards to about 0·1 ampère, and at this stage the furnace temperature was steadied, and a constant ionisation current was obtained for over an hour, in fact, until the experiment was arrested. The potential difference which developed between the electrodes during this time amounted to 1·8 volts.

While the large negative maximum was being recorded we noted that the blue flame of the escaping gases from the furnace tube was tinged yellowish—an effect attributed to silica vapour which was carried along with the stream of gas. The yellow colour disappeared when the current dropped to its steady value.

On a second run with the same apparatus neither positive rays nor a negative maximum was observed.

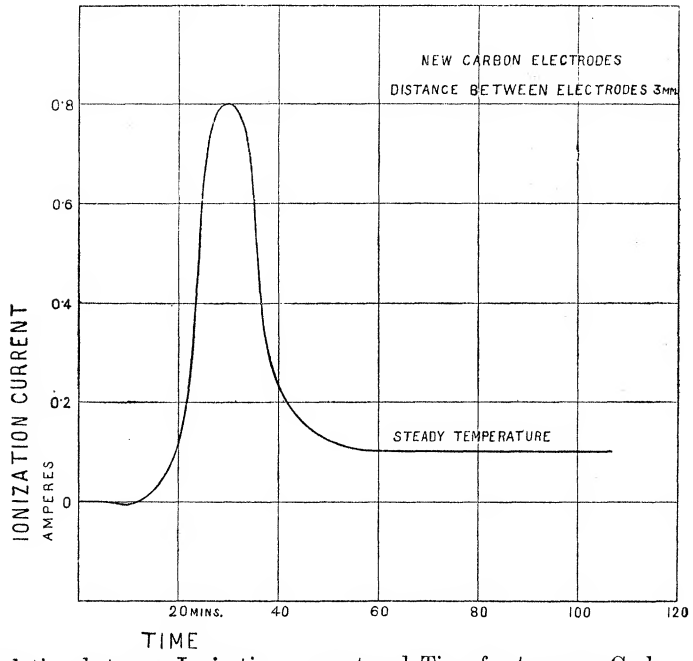

FIG. 7.—Relation between Ionisation current and Time for two new Carbon Electrodes, one hot, the other water-cooled. No potential was applied. The temperature was rising for the first 50 minutes and was afterwards steady.

Discussion.

Although we have not as yet any definite knowledge of the nature of the carriers of electricity concerned in the foregoing experiments, we should like to offer a few comments on the results. It may be that these carriers are almost wholly sputtered solid matter and that corpuscles do not play a great part in the phenomena as they do at low pressures. According to Richardson, the ionisation currents obtained with carbon in high vacua are due solely to the emission of corpuscles; the only part the surrounding gas plays is to become ionised by collision and so augment the current. In some of the present experiments no potential was applied to the electrodes, and if the corpuscles owe their velocity of emission only to the temperature, such velocity at 3000° C., for example, is about 3×10^7 cm. per second* (assuming with J. J. Thomson the applicability of the gas laws and the kinetic theory to the unattached electrons which are disseminated through solids). This speed is a very slow one: corpuscles liberated by ultra-violet light are more than 10 times, cathode rays over 100 times and some β-rays nearly 1000 times as fast. In gases at atmospheric pressure the free path of such

* Equivalent to a potential fall of about $\frac{1}{4}$ volt.

unencumbered electrons would be very small indeed, and their ability to ionise by collision would be negligible according to present theory. We have, of course, to remember that a rise of temperature produces a fall of density, with a corresponding increase in the free path, *e.g.*, at 2000° C. the "effective" pressure is reduced to about 1/8th; at 3000° C. to 1/11th. Experiments with a vacuum furnace would probably throw much light on the matter, and such experiments are now in progress in a furnace in which the prevailing pressure can be adjusted to any desired value.

As we have remarked elsewhere, our largest ionisation currents appear to be associated with the expulsion of impurities in the carbon, and probably the magnitude of the effects would be modified if impurities were wholly absent.

Carbon has the faculty of holding tenaciously enormous amounts of foreign matter, particularly occluded gases, and if the evolution of these impurities* goes hand in hand with the emission of negative electricity some ultimate steady fatiguing of the carbon should be found. Our experience does not enable us to say whether this is so; up to now we have noticed nothing of the kind. Much the same ideas have been expressed by Messrs. Pring and Parker in their paper already referred to. In this connection reference should be made to an important paper by W. C. Arsem in vol. 20 of the 'Transactions of the American Electrochemical Society,' in which the relation between the rate of graphitisation of carbon and its contained impurities is thoroughly studied. The view hitherto held that graphitisation of carbon is generally accelerated by the presence of impurities such as iron oxide derives no support from his experiments.

Apropos of the effect of impurities, the large currents obtained by Richardson with an over-run carbon glow-lamp may be largely due to the ejection at such a high temperature of the various impurities contained in the carbon and binding material of the filament. It is well known that, in lamp practice, it is only of recent years that it has become customary to heat carbon filaments either before or after mounting (except during the flashing process) to much more than about 1700° C., at which temperature some of the possible contained impurities are only slightly volatile. We hope to repeat all the present experiments with spectroscopically pure carbon and graphite.

In considering the chemical side of the phenomena described in this paper, it should be remembered that the relative activity of various gases

* Cunningham ('Phil. Mag.,' 1905, vol. 9, p. 193) found that an electric discharge at low pressures was transmitted more easily by nitrogen freshly expelled from carbon than by ordinary nitrogen.

changes rapidly with temperature. For example, CO_2 at 2500° behaves as an energetic supporter of combustion, and acts on carbon not very differently from oxygen at low temperatures. Nitrogen, which at ordinary temperatures is regarded as inactive, becomes, at high temperature, an agent of attack for many metals and other substances. Many compounds, such as steam, cannot exist at really high temperatures, and are probably completely dissociated.

It may be noticed, in passing, that the experiments set out above, in which no potential was applied, afford an interesting example of the Thomson effect for a vapour. The currents brought about by the potential gradient flow in the direction opposite to the heat flow. In the case of carbon "vapour" this agrees with what is known for the solid. It is worth recording that the atmosphere of the furnace appeared, as far as could be seen, to be perfectly clear when the carbon "vapour" was crossing the space between the electrodes.

It would at once occur to anyone who had been occupied with considerations such as have been detailed in this paper that it might be possible to construct on some such lines a generator of electricity which would depend directly upon combustion at high temperatures; and, naturally, this is an aspect of the question of which we have not lost sight.

Summary.

An investigation into the electrical properties of the atmospheres of carbon-tube resistance furnaces has been undertaken at temperatures from 1500° to 3000° C., and at atmospheric pressure.

(1) Potential-current curves have been derived by the use of two exploring electrodes of carbon or graphite. At high temperatures, currents up to 10 ampères were obtained with the application of quite small potential differences (up to 8 volts) between the electrodes. The ionisation increases exponentially with the temperature.

(2) In the absence of any applied potential a reversible transient electric current was obtained by keeping one of the electrodes fixed in the furnace and heating or cooling the other electrode by moving it in or out of the hot region of the furnace. The highest current thus obtained was nearly 2 ampères. The production of an alternating current was thus rendered possible by the use of a suitable periodic device.

(3) If both electrodes are stationary in the furnace and one is kept permanently hot and the other (by water-cooling) permanently cold, a continuous current can be maintained without applying potential, *e.g.*, a steady current of 0·8 ampère has been obtained for a few minutes, and 0·1 ampère for over an

hour. These are "negative" currents, *i.e.* they flow from the cold to the hot electrode across the gap. Their magnitude is somewhat greater in hydrogen than in nitrogen.

(4) These large negative currents appear to be intimately associated with the transit across the electrode gap, first of the impurities in the carbon, and afterwards of the carbon itself.

(5) Small "positive" currents of a few micro-ampères have been detected with new (but not with old) carbon electrodes at the lower stages of the heating.

(6) Some of these effects have also been obtained from non-electric sources of heat.

The Wave-Problem of Cauchy and Poisson for Finite Depth and slightly Compressible Fluid.

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(Communicated by Prof. A. E. H. Love, F.R.S. Received February 1,—Read February 22, 1912.)

1. *Introduction.*

The present paper is in some respects a completion of a former paper* on water waves resulting from a given disturbance. The following article is devoted to a numerical discussion of a solution, previously given, of the normal Cauchy-Poisson problem for finite constant depth of fluid. The last part of the paper contains a detailed treatment of compressible fluids, with a view to elucidating the initial stages of the spreading out of a disturbance initially confined to a limited region of the fluid. It is found that a very general case of propagation is capable of formal solution.

2. *Numerical Discussion of the Cauchy-Poisson Problem for Finite Depth.*

The serial solution given in the previous paper lends itself to a certain extent to numerical treatment, though not so well as for the case of infinite depth, which has been so completely discussed by Lamb.† In the general case there does not seem to be any general transformation to facilitate the calculation, so that we have to rely on the direct use of the series. The solution referred to may be briefly recapitulated as follows:—

* 'Roy. Soc. Proc.,' A, 1910, vol. 83, p. 347.

† H. Lamb, 'Proc. Lond. Math. Soc.,' Series 2, 1904, vol. 2, p. 371.